

X-Ray Observations of the Galactic Center with Suzaku

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Received 30 May 2005, accepted 11 Nov 2005

Published online later

Key words Galactic Center, X-ray, FeK α lines

We report on the diffuse X-ray emissions from the Galactic center (GCDX) observed with the X-ray Imaging Spectrometer (XIS) on board the Suzaku satellite. The highly accurate energy calibrations and extremely low background of the XIS provide many new facts on the GCDX. These are (1) the origin of the 6.7/7.0 keV lines is collisional excitation in hot plasma, (2) new SNR and super-bubble candidates are found, (3) most of the 6.4 keV line is fluorescence by X-rays, and (4) time variability of the 6.4 keV line is found from the Sgr B2 complex.

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1 Introduction

The iron K-shell complex in the Galactic center diffuse X-rays (GCDX) is composed of four lines at 6.4, 6.7, 7.0 and 7.1 keV (Koyama et al. 1986). These are K α lines of neutral(FeI), He-like (FeXXV) and H-like (FeXXVI) iron, and K β line of neutral iron (FeI). The origin of these iron lines or the origin of the GCDX has been a big problem. In order to solve the problem, high quality data of the iron K-shell lines are essentially important. Using the X-ray Imaging Spectrometer (XIS) (Koyama et al. 2007a) on board Suzaku (Mitsuda et al. 2007), we have obtained accurate X-ray spectra in the hard X-ray band including these key lines. This paper reports on the line analysis and discussion on these observational data.

2 Observations and Data Reduction

The Galactic center regions were observed with the XIS (Koyama et al. 2007a) on board the Suzaku satellite (Mitsuda et al. 2007). The observations are composed of several mosaic positions, each of ~ 100 ks exposure. We have made comprehensive energy calibrations on the whole imaging region of the CCDs on the XIS (for details, see Koyama et al. 2007d). The reliability of the energy scale is demonstrated in table 1. The K α lines of SXVI, FeXXVI and MnI (the calibration line) have simple structure compared to that of the K α complex of FeXXV, and hence are reliably determined independent of emission mechanisms. As are given in table 1, the observed line energies of K α of SXVI and FeXXVI are within a few eV from the predicted energies of these lines. Also MnIK α is determined within a few eV from the laboratory (predicted) energy. We therefore con-

Table 1: The observed and laboratory energies

H-like atom	Observed (eV)	Lab(eV)	δ (eV)
SXVIK α	2622^{+4}_{-3}	2622	0
FeXXVIK α	6970^{+3}_{-2}	6966	4
MnIK α	5900^{+2}_{-1}	5895	5

clude that the energy scale is reliable within 5 eV in the 6–7 keV energy band.

3 Origin of the 6.7 keV and 7.0 keV Lines

The X-ray spectrum from the GC region exhibits many emission lines. The most prominent line in the low energy band is K α of SXV at 2.45 keV. In the high energy band, strong line-complex near at 6–7 keV is notable. These are K α lines of FeI, FeXXV and FeXXVI, and K β of FeI at the energies of 6.4, 6.7, 7.0 and 7.1 keV, respectively.

What is the origin of the 6.7 keV (K α of FeXXV) line? Is this due to collisional excitation (CE) or charge exchange (CX)? These two processes (CE and CX) produce different line ratio of the resonance and forbidden lines in the fine structure of the K α line complex of FeXXV, and hence the center energy of the 6.7 keV line is slightly different with each other. The laboratory experiments found that CX gives the center energy at 6666 eV, while CE is 6680–6685 eV (Wargelin et al. 2005). We made a very accurate spectrum of the GCDX in the hard energy band up to ≥ 10 keV (figure 1). The observed line energy in the GCDX (figure 1) is determined to be 6680 ± 1 eV (systematic error is ± 5 eV), very close to CE of 6680–6685 eV and significantly higher than that predicted by CX (6666 eV).

We detected narrow FeXXVIK α (Ly α) line at 7.0 keV. If the 7.0 keV line is due to CX, strong bump should appear at the Lyman series limit around 9–10 keV (the Lyman series

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Table 2 The plasma temperatures determined from the line flux ratios and the energy centroid of the 6.7 keV line

Ionization Temperature (keV)	
FeXXVI $K\alpha$ /FeXXV $K\alpha$	$6.5^{+0.1}_{-0.1}$
FeXXVI $K\beta$ /FeXXV $K\beta$	$5.1^{+1.5}_{-1.0}$
NiXXVIII $K\alpha$ /NiXXVII $K\alpha$	$9.3^{+1.6}_{-2.5}$
Centroid of FeXXV $K\alpha$	2.5 – 6.5
Electron Temperature (keV)	
FeXXV $K\beta$ /FeXXV $K\alpha$	6.2^{+3}_{-1}
FeXXVI $K\beta$ /FeXXVI $K\alpha$	≥ 6.5 (lower limit)

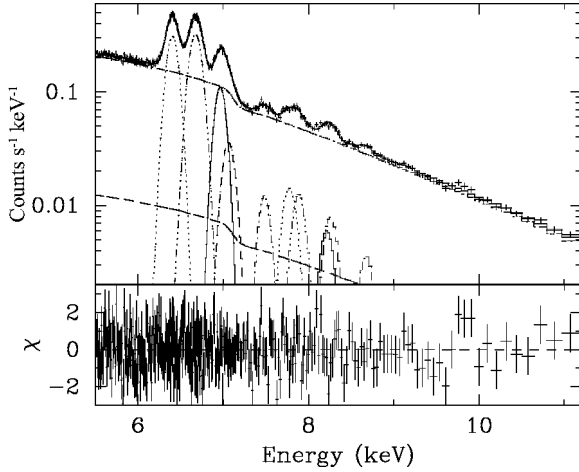


Fig. 1 The energy spectrum of the GCDX in the high energy band (adopted from Koyama et al. 2007d). Four intense lines at 6–7 keV are $K\alpha$ of FeI, FeXXV and FeXXVI, and $K\beta$ of FeI, while weak lines at around 7–9 keV are $K\alpha$ of NiI and NiXXVII, and $K\beta$ of FeXXV.

transition of $n \geq 8 \rightarrow n = 1$). The very low background of the XIS around 7–12 keV, the energy band above the iron $K\alpha$ complex, enable us to check the structure of the Lyman series limit. We see no bump at 9–10 keV in figure 1, which excludes CX origin. Thus the origin of the 6.7 and 7.0 keV line is likely to be a CE process, or the X-rays are due to a high temperature plasma.

We then discuss the plasma structure. Ionization temperature (T_i) is determined by the ratio of $K\alpha$ lines from He-like and H-like atoms, while the electron temperature (T_e) is determined by the ratio of $K\alpha$ and $K\beta$ lines from the same atom in the same ionization state. Since the FeXXVI $K\alpha$ and FeXXV $K\beta$ lines are near the iron K-edge, the fluxes are strongly coupled to the depth of the K-edge. The depth of the K-edge structure can be precisely constrained by the very low background data at 7–12 keV. Figure 1 demonstrates that these line fluxes are determined very accurately due to the accurate and the low background flux level above the 7 keV band.

The derived temperatures from the observed line flux ratios are given in table 2. We note that electron temperature has been usually determined from the continuum shape assuming a thermal bremsstrahlung model. This method, how-

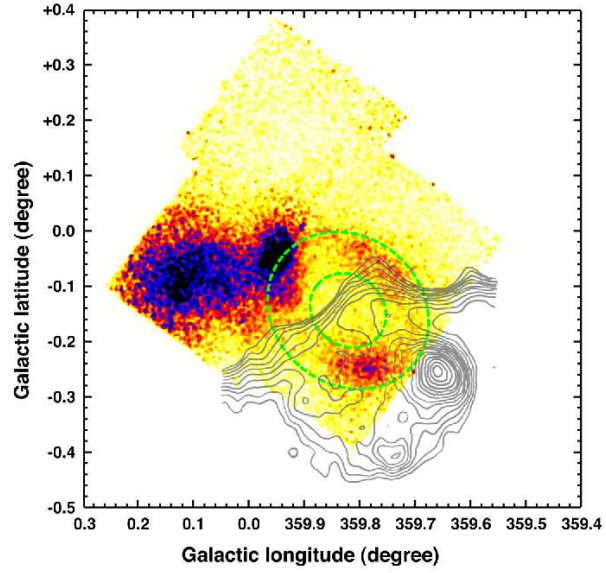


Fig. 2 The 2.45 keV (Sxv $K\alpha$) band image overlaid on the 10 GHz band contour (light gray solid lines: Sofue 1988). The new X-ray SNR candidate G 359.79–0.26 is located at the center of the radio shell. A large ring-like structure is shown by the green-dashed annulus (adopted from Mori et al. 2007).

ever, may have large errors if the continuum is contaminated by a non-thermal emission. Our new method to determine the electron temperature by the ratio of $K\alpha$ and $K\beta$ lines from the same atom in the same ionization state, is free from any contribution of a non-thermal component.

Since the energy centroid of the FeXXV $K\alpha$ moves with the ionization temperature due to the contamination of the satellite lines, we can also determine the temperature from the observed center energy. The result is also given in table 2. We see that all the results are consistent with the plasma of ~ 6.5 keV temperature in collisional ionization equilibrium (CIE).

4 Discovery of New SNRs

Since the He-like $K\alpha$ lines are prominent in high temperature plasmas such as SNRs, we searched for SNR candidates using the FeXXV $K\alpha$ (6.7 keV) and Sxv $K\alpha$ (2.45 keV) lines. In the 6.7 keV band, we found two bright spots, Sgr A East (Koyama et al. 2007c) and G 0.61+0.01 (Koyama et al. 2007b). The temperatures of these SNRs (3–4 keV) are higher than any other young SNRs, probably due to extreme environmental conditions in the GC regions.

In the 2.45 keV band, we also found several bright spots, which may also be young SNRs of moderate temperature (~ 1 keV). All the SNR candidates have absorptions of $(0.4-1) \times 10^{23} \text{ cm}^{-2}$. These values are the same as the interstellar absorption toward the GC region, hence these SNR candidates are located near at the GC region.

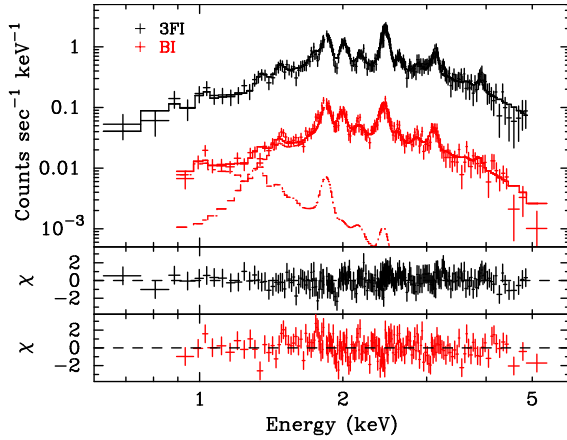


Fig. 3 The X-ray spectra of a new SNR candidate, G 359.79–0.26 at the southeast of the Galactic center (adopted from Mori et al. 2007).

We show a bright spot at $(l, b) = (359^\circ.79, -0^\circ.26)$ (G 359.79–0.26; Mori et al. 2007) in figure 2. G 359.79–0.26 is a strong candidate of SNR, because it is also associated with a radio ring structure (Sofue 1988). The X-ray spectrum of G 359.79–0.26 is given in figure 3. It is fitted with a thermal plasma model of ~ 1 -keV temperature.

In addition to the SNR candidates, we discovered large ring/arc structures. In figure 2, we see a large ring with a 10 arcmin radius with the center at $(l, b) = (359^\circ.81, -0^\circ.14)$. G 359.79–0.26 is a part of this large ring. The real size of the ring is about 20-pc radius at the Galactic center distance of 8 kpc. Therefore this ring would be a super-bubble. Another super-bubble candidate is a faint arc in the positive Galactic latitude emerging from Sgr C ($l = 359^\circ.45$) to the positive Galactic latitude into the Galactic center with a radius of 30 arcmin. To confirm this faint structure, however, deep exposure observations are required.

5 The 6.4 keV Clumps

Figure 4 is the 6.4 keV line map. We see many clumps. The spectra from these clumps exhibit not only a strong 6.4 keV line but also a 7.1 keV line, which are $K\alpha$ and $K\beta$ line from a neutral or low ionization Fe atoms. The flux ratio is about 0.1, consistent with fluorescence from a neutral Fe (FeI).

What is the origin of the 6.4 keV clumps? Is this due to inner shell ionization by electrons or X-rays? In table 3, we list the equivalent width (EW) of the 6.4 keV line and absorption depth (N_H) for the inner shell ionization by electrons and X-rays. From the spectrum analysis, we found that most of the 6.4 keV clumps have large EW in the range of 1–2 keV, which are consistent with the fluorescence by X-ray irradiations (see table 3). The K-edge absorptions (N_H) are in the range of $(2-10) \times 10^{23} \text{ cm}^{-2}$, which are larger than the interstellar absorption to the GC. The large N_H is also consistent with the fluorescence by X-rays (see table 3). We, therefore conclude that most of the 6.4 keV clumps, if not all, are produced by X-ray irradiations.

Table 3 Inner shell ionization by electrons and X-rays

Parameter	Electrons	X-ray
EW (keV)	0.3–0.6	1–2
N_H (cm^{-2})	10^{21}	10^{24}

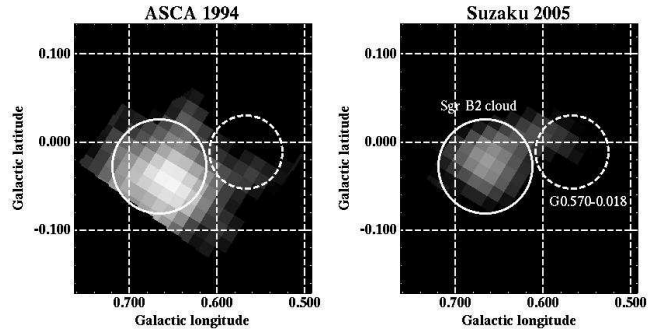


Fig. 5 The surface brightness maps of the 6.7 + 6.4 keV lines obtained with the ASCA SIS and the Suzaku XIS (adopted from Inui et al. 2007).

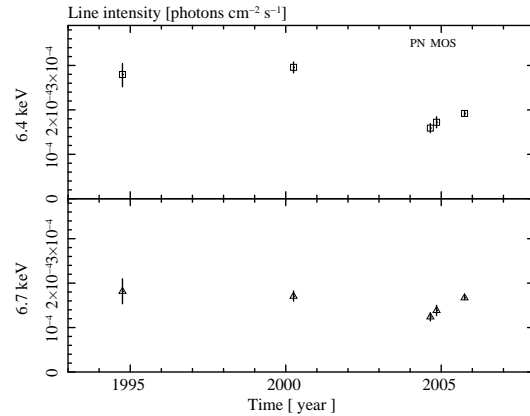


Fig. 6 The time history of the 6.4 keV and 6.7 keV line fluxes in the Sgr B2 region (adopted from Inui et al. 2007).

6 Time Variability of the Sgr B2 complex

A concrete fact to favor the X-ray irradiation origin would be time variability of the 6.4 keV line. In order to examine the 6.4 keV line flux, we made the surface brightness map of the iron lines in the ASCA (1994) and Suzaku (2005) observations (Koyama et al. 2007e, Inui et al. 2007). Since the energy resolution of ASCA was not good enough to separate the 6.4 keV line from the 6.7 keV line, we made images in the 6–7 keV band subtracting the continuum flux (figure 5). We see clear decrease of the surface brightness from the ASCA to the Suzaku observations.

In order to see the flux change of the 6.4 keV line quantitatively, we made the X-ray spectra of the ASCA (1994), Chandra (2000), XMM-Newton (2004) and Suzaku (2005) observations near the Sgr B2 cloud. The spectra exhibit three pronounced peaks which represent FeI $K\alpha$ (6.4 keV) and

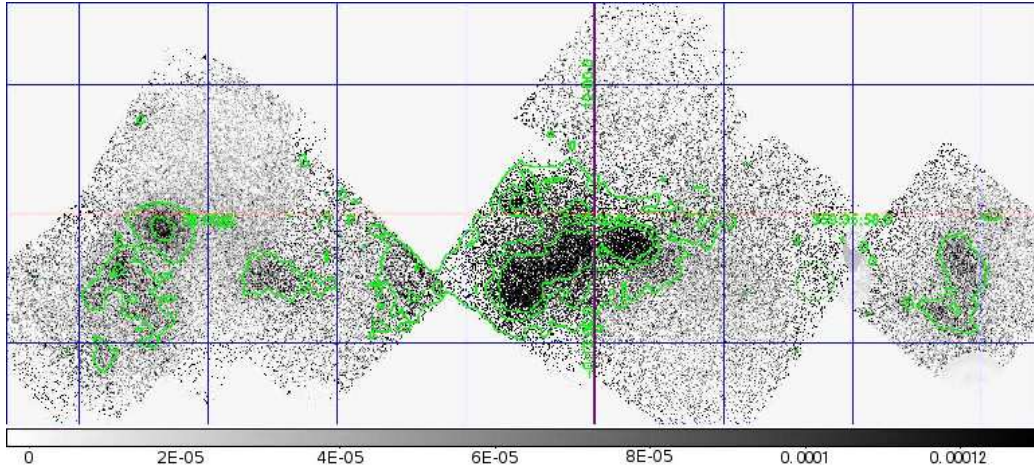


Fig. 4 The 6.4 keV (FeI $K\alpha$) map. The grid is the Galactic coordinate with the spacing of 0.2 degree

FeXXV $K\alpha$ (6.7 keV) lines, and the composite of FeXXVI $K\alpha$ (7.0 keV) and FeI $K\beta$ (7.1 keV) lines.

Since the Suzaku spectrum has the best statistics with accurate line energy (Koyama et al. 2007d), we fit the Suzaku spectrum with a model of a power-law plus four Gaussian lines, fixing the energy gap between FeI $K\alpha$ (6400 eV) and FeI $K\beta$ (7058 eV) to the theoretical value (+658 eV) (Kaastra and Meve 1993). The line flux ratio of FeXXVI $K\alpha$ /FeXXV $K\alpha$ is fixed to be 0.3. This ratio is slightly smaller than that found in the GCDX (Koyama et al. 2007d), because our selected region includes a SNR candidate G 0.61 \pm 0.01, a strong 6.7 keV source (Koyama et al. 2007b).

Then we fit the spectra of the other satellites, fixing the power-law index, N_H , the line center energies, and the flux ratio between the FeI $K\alpha$ and FeI $K\beta$ lines to those of the Suzaku best-fit parameters. The best-fit fluxes of the 6.4 keV and 6.7 keV lines from all the satellites are given in figure 6 as a function of observed years.

From figure 6, we see that the 6.7 keV line is almost constant. This is very reasonable because the 6.7 keV line is due to the largely extended GCDX. In other words, no time variability of the 6.7 keV line flux confirms the reliability of the cross-calibration in the line flux of each satellite. Based on this reliable cross-calibration, we firmly conclude that the 6.4 keV line flux has been significantly variable, the fluxes in the XMM-Suzaku period is 2/3 of that in the ASCA-Chandra era.

The linear size across the Sgr B2 complex is about 40 light-years, but the brightest part (Sgr B2) is \sim 10 light-years. The time scale of the 6.4 keV flux change is also \sim 10 years, comparable to the light-crossing time of the cloud. Any charged particle (with a finite mass) can not move as fast as the speed of light, and hence can not produce such a rapid and large scale variability.

A unique scenario to explain the spectral features and the fast time variability of the 6.4 keV lines is that the Sgr B2 cloud absorbs variable X-rays above the 7.1 keV edge energies and simultaneously re-emits the fluorescent 6.4 keV lines. Where is the bright variable X-ray source? Is this

a transient source located near the Sgr B2 complex? This putative transient source must be brighter than 10^{37} ergs s $^{-1}$ for more than 10 years with the flux variability of a factor 1.5, which is very unlikely.

The most probable source to exhibit the bright and relatively long-lived X-rays is a massive black hole Sgr A*. About 300 years ago, the X-ray from Sgr A* was 10^6 times brighter than the present value, and decayed to about 2/3 after \sim 10 years. The X-rays hit the Sgr B2 cloud after \sim 300-years travel. The cloud re-emits the 6.4 keV photons. Like a time delayed-echo, the X-ray is now just arriving at the Earth, when Sgr A* becomes quiet.

Acknowledgements

We would like to thank H. Nakajima, H. Uchiyama, and Y. Takikawa for their efforts in the Galactic center data analysis. This work is supported by the Grant-in-Aid for the 21st Century COE “Center for Diversity and Universality in Physics” from Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

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